



# Aeroelastic Prediction Workshop #3

## Welcome and Introduction

Pawel Chwalowski

Aeroelasticity Branch, NASA Langley Research Center,  
Hampton, VA, USA

21 - 22 January 2023

<https://nescacademy.nasa.gov/workshops/AePW3/public>

# AePW-3 Workshop Agenda, Day 1, Saturday, January 21, 2023



7:00	Registration	
7:00 – 8:00	Breakfast (provided)	
8:00	01	Welcome / Overview: Pawel Chwalowski
8:45	02	Development of a Benchmark Model: A Tale of Two Models: Walt Silva
9:30	Break, 15 minutes (coffee and tea)	
9:45	03	Flight Test WG Overview / Flight Data: Jeff Ouellette
10:00	04	1 hour / 5 presentations / 15 minutes each / summary discussion
11:30	Lunch, 1.5 hours (on your own)	
13:00	05	High Angle WG Overview: Pawel Chwalowski
13:30	06	BSCW Shock Buffet: 2 hours / 4 presentations / 15 minutes
15:30	Break, 15 minutes (coffee and tea)	
15:45	07	BSCW Flutter: 2 hours / 6 presentations / 15 minutes each + summary
17:45	Adjourn	

# AePW-3 Workshop Agenda, Day 1, Saturday, January 21, 2023

## Flight Test Working Group



9:45	03	<b>Flight Test WG Overview / Flight Data: Jeff Ouellette</b>
10:00		FUN3D LFD: Steve Massey, NASA
10:20		ZAERO, ENSOLV: Jos Aalbers
10:40		SysID (flight data): Jared Grauer
11:00		NASTRAN, LOES, summary: Jeffrey Ouellette
11:30		Lunch (on your own)

# AePW-3 Workshop Agenda, Day 1, Saturday, January 21, 2023

11:30	Lunch, 1.5 hours (on your own)	
13:00	05	High Angle WG Overview: Pawel Chwalowski
13:30	06	BSCW Shock Buffet:
13:30		Indian Institute of Science
13:45		The University of Newcastle
14:00		Technion
14:15		NASA
	USAFA (contributing data)	
14:30		Summary
15:00	Break, 15 minutes (coffee and tea)	
15:15	07	BSCW Flutter:
15:15		Technion
15:30		CREATE-AV
15:45		UZ
	USAFA	
	BAE	
16:00		NASA
16:15		Summary
17:00		Adjourn



# AePW-3 Workshop Agenda, Day 2, Sunday, January 22, 2023



7:00		Registration
7:00 – 8:00		Breakfast (provided)
8:00	08	Welcome / Overview: Pawel Chwalowski
8:15	09	High Deflection WG Overview / Experimental Data: Markus Ritter
8:45	10	1 hour / 4 presentations / 15 minutes each
9:45		Break, 15 minutes (coffee and tea)
10:00	11	1.5 hours / 6 presentations / 15 minutes each + summary
11:30		Lunch, 1.25 hours (on your own)
12:45	12	High Speed WG Overview / Experimental Data: Eric Blades
13:15	13	HyMAX: 1.5 hours / 6 presentations / 15 minutes each
14:45		Break, 15 minutes (coffee and tea)
15:00	14	RC-19: 1.5 hours / 6 presentations / 15 minutes each + summary
16:30		Break, 15 minutes
16:45	15	Future Direction for AePW / General Discussion: All
18:30		Adjourn

# AePW-3 Workshop Agenda, Day 2, Sunday, January 22, 2023



7:00	Registration
7:00 – 8:00	Breakfast (provided)
8:00	08 Welcome / Overview: Pawel Chwalowski
8:15	09 High Deflection WG Overview / Experimental Data: Markus Ritter, Daniella Raveh
8:30	University of Michigan, Georgia Tech
8:45	Technion
9:00	University of São Paulo
9:15	Imperial College
9:30	DLR
9:45	Break (Coffee and Tea)
10:00	TU Delft
10:15	NASA
10:30	Metacomp Technologies Inc.
10:45	Siemens Belgium
11:00	SIMULIA Aerospace & Defense
11:15	Summary (30 minutes)
11:45	Lunch (on your own) 1.5 h

# AePW-3 Organizing Committee



Daniella Raveh, Technion

Carlos Cesnik, University of Michigan

Markus Ritter, DLR

Adam Jirasek, USAFA

Eric Blades, ATA Engineering

Jeff Ouellette, NASA Armstrong

Walter Silva, NASA Langley

Alex Chin, NASA Langley

Bret Stanford, NASA Langley

Pawel Chwalowski, NASA Langley

# Tacoma Narrows Bridge, 1940





# Tacoma Narrows Bridge, November 7, 1940

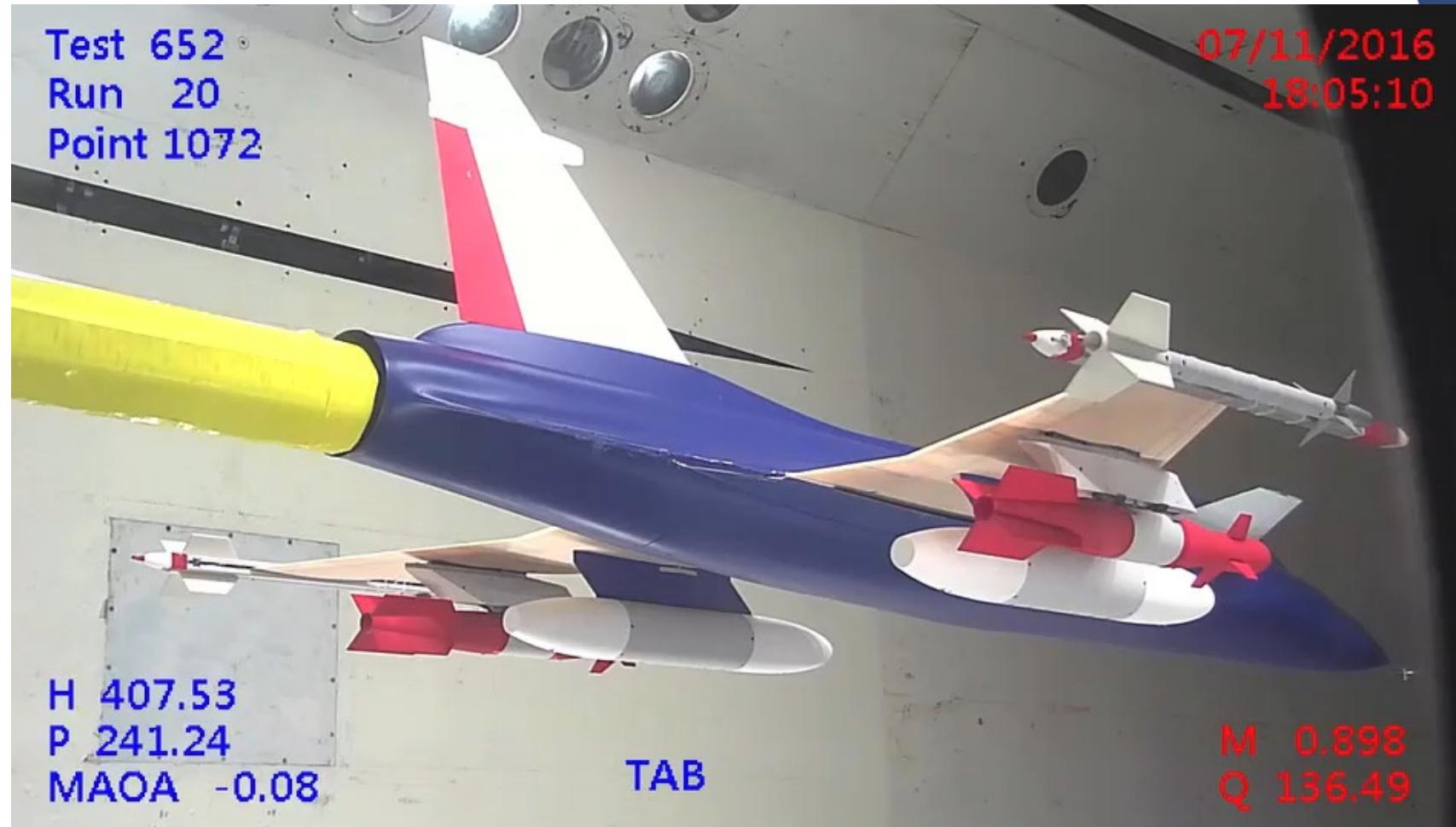


- 42 mph cross-wind
- Failure event:
  - Twisting oscillations
  - Frequency: 1 oscillation every 5 seconds
- Post-failure wind tunnel testing:
  - The bridge cross section shown as highly vulnerable to being unstable
- The phenomena most likely to have caused the event:  
**Flutter involving Separated Flow Coupled to a Torsionally Weak Structure**

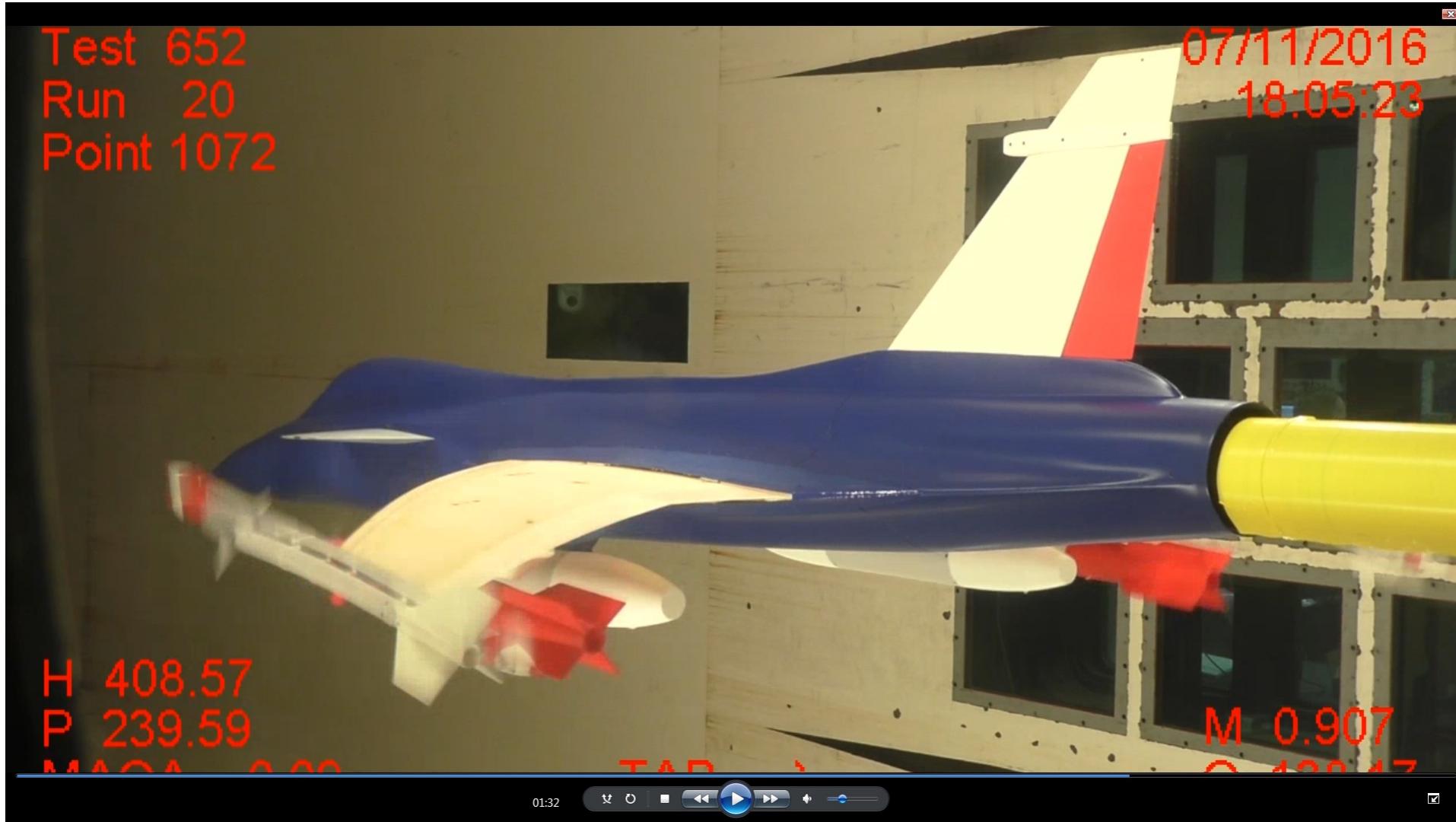
# KTH Flutter Testing: View from the Control Room



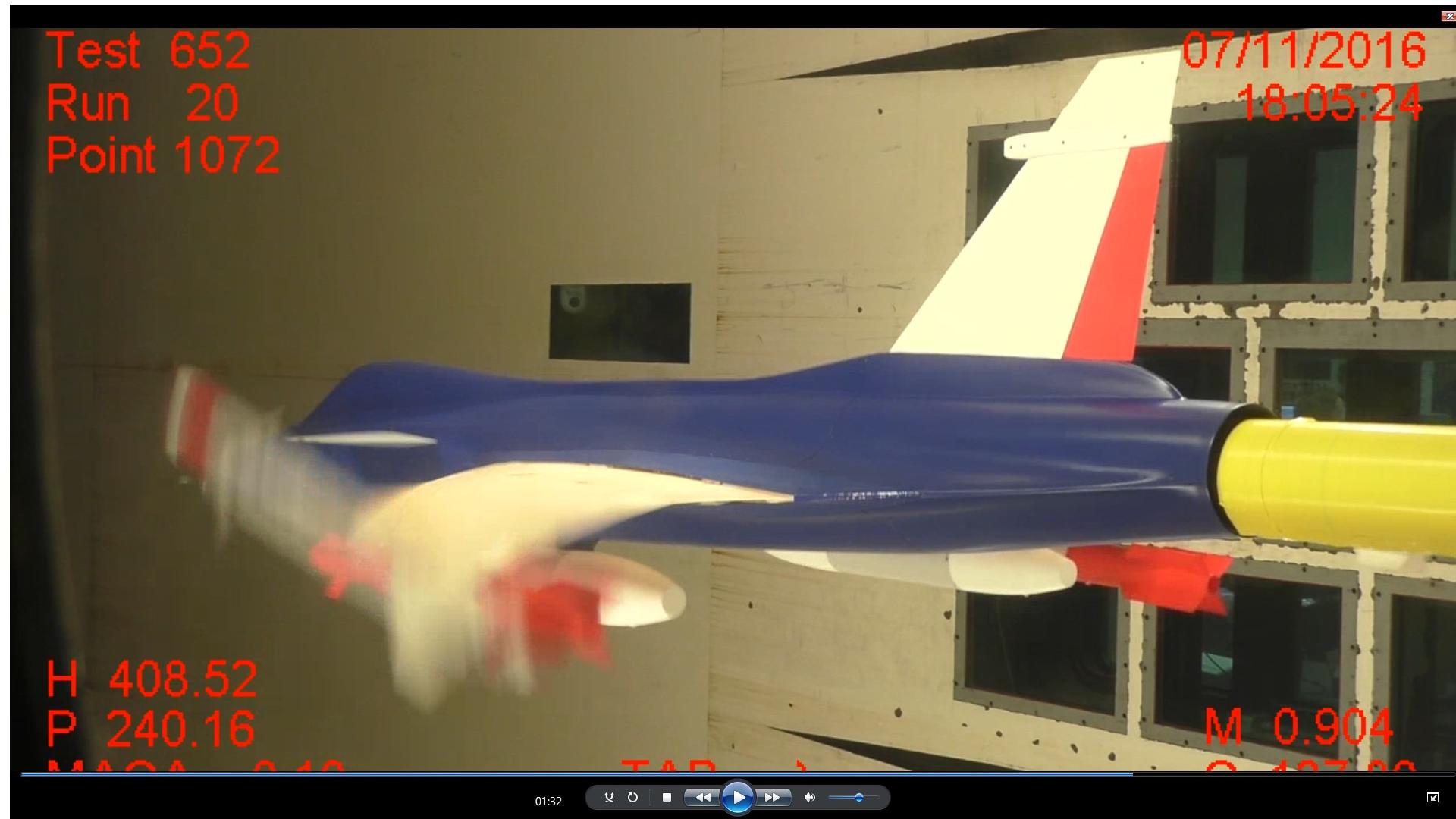
- Test
  - Transonic Dynamics Tunnel (TDT)
  - NASA Langley Research Center
  - June-July 2016
- Objective:
  - Obtain experimental data for nonlinear flutter mechanisms



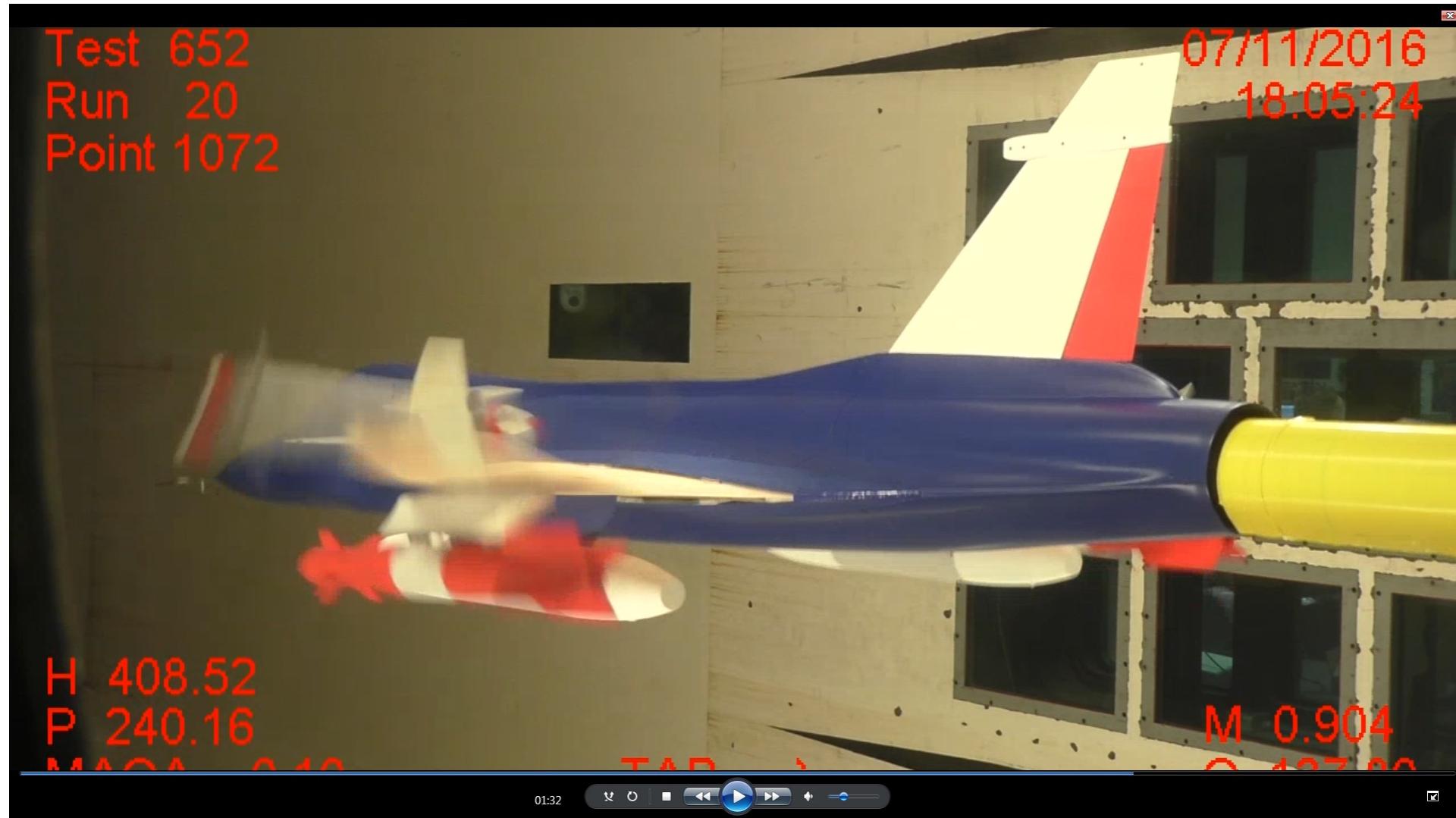
# KTH Flutter Testing: View from Sting-mounted Camera



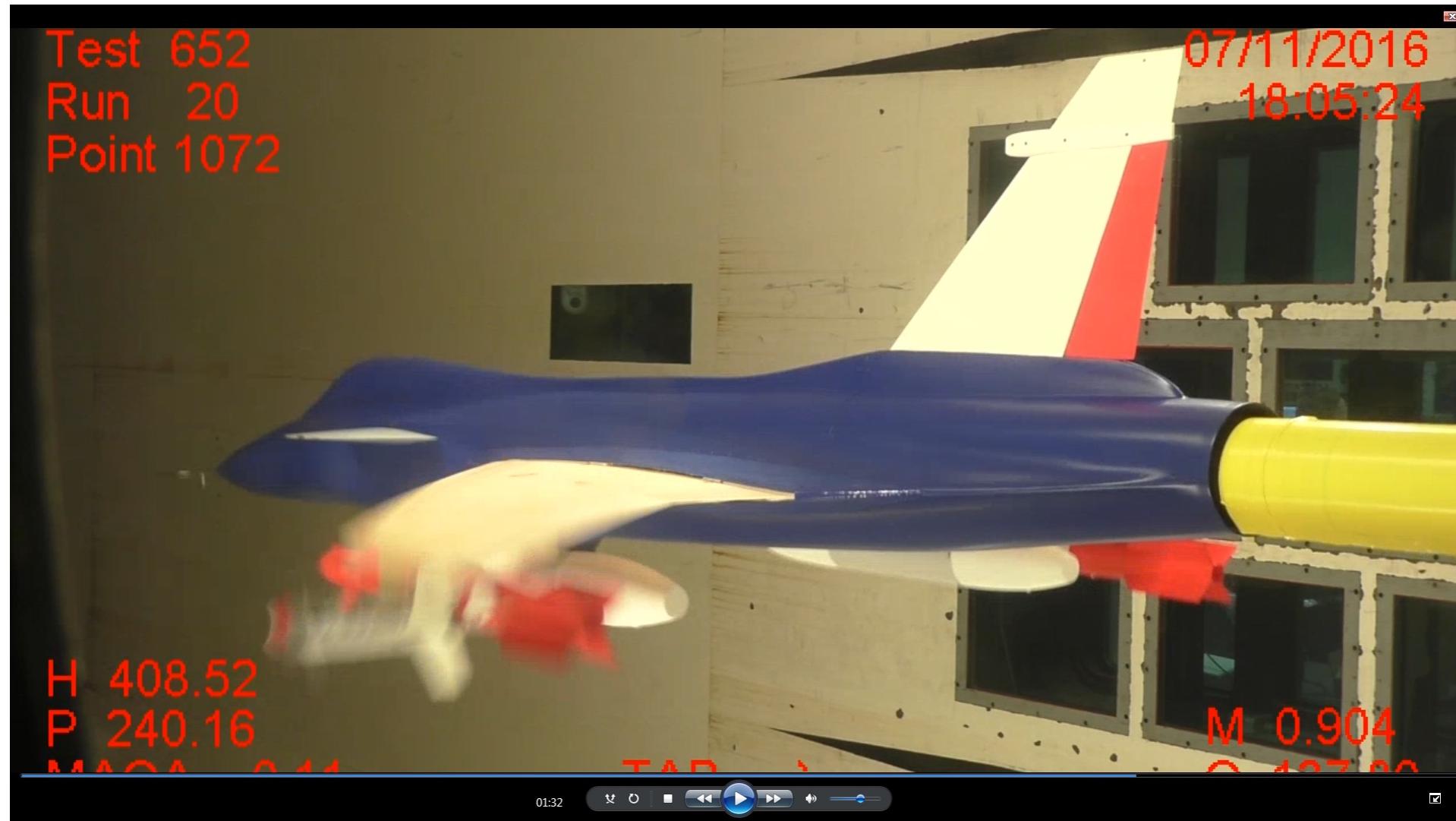
# KTH Flutter Testing: View from Sting-mounted Camera



# KTH Flutter Testing: View from Sting-mounted Camera



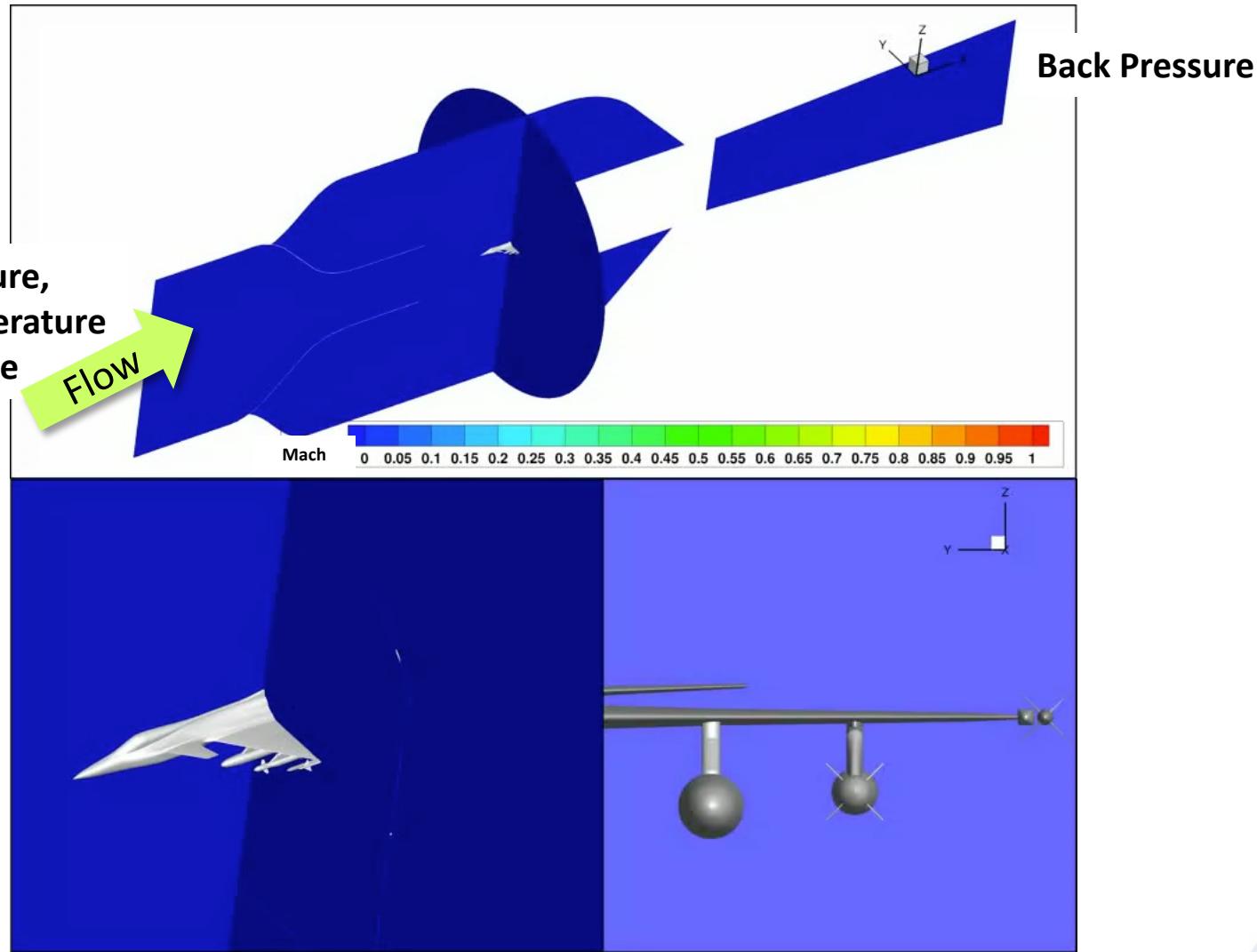
# KTH Flutter Testing: View from Sting-mounted Camera



# Animation of KTH Flutter using FUN3D



- Total Pressure,
- Total Temperature
- Inflow Angle



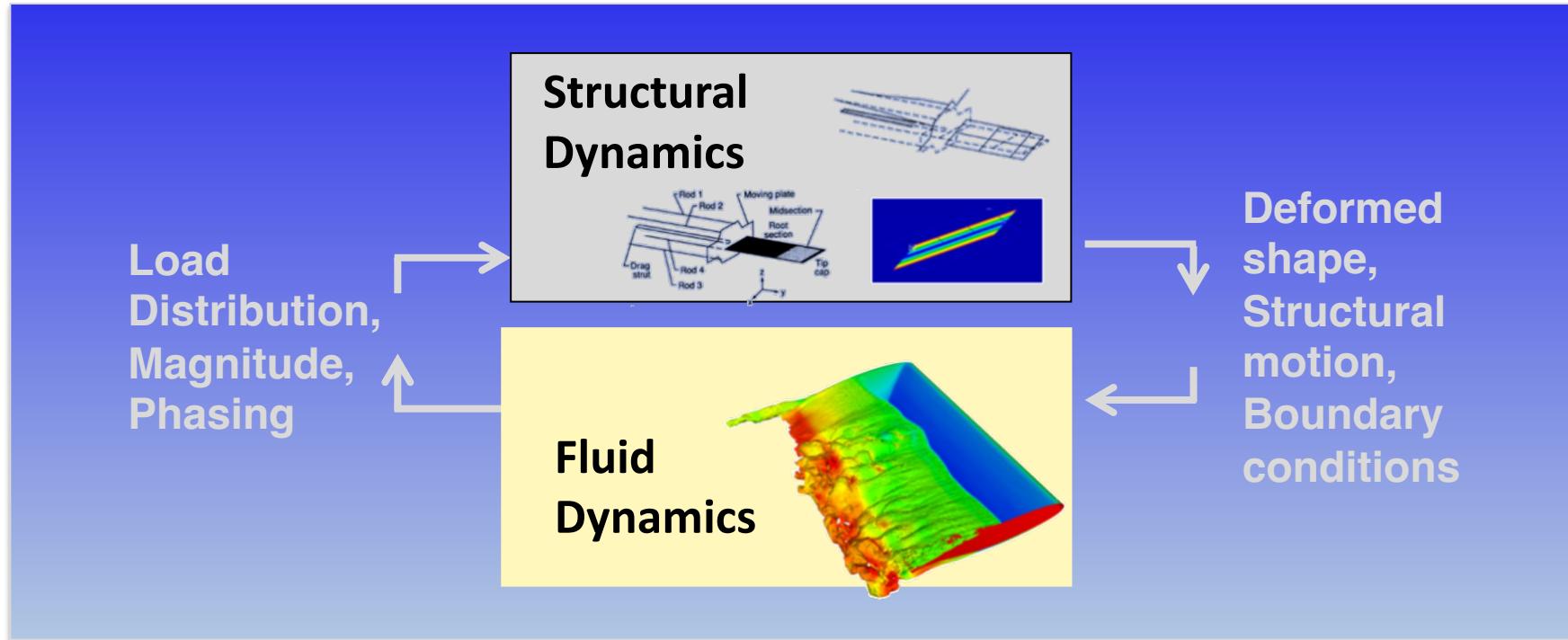


- **Assess the goodness of computational tools** for predicting aeroelastic phenomena, including flutter
- **Understand why** our tools don't always produce successful predictions
  - Which **aspects of the physics** are we falling short of predicting correctly?
  - What about our **methods** causes us to fall short of successful predictions?
- Establish **uncertainty bounds** for computational results
- Establish **best practices** for using tools
- Explicitly **illustrate the specific requirements on a validation experiment**
- Establish **AePW community** for leveraging experiences and processes
- Ratify **Building Block Approach** in AePW series

## Fundamental hindrance to this challenge

- **No sufficient aeroelastic benchmarking validation standard exists**

# AePW Building Block Approach to Validation



**AePW-1: Focus on unsteady fluid dynamics**

# Configurations / Data Sets Selected

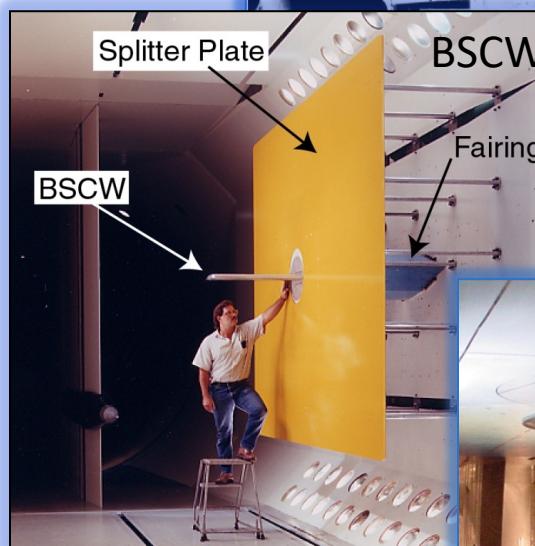


- Perceived Simplicity & Complexity
  - Geometric
  - Flow Physics
- All configurations have
  - Transonic flow
  - Unsteady pressure data
  - Forced oscillation data
- Availability
  - Distribution unrestricted



RSW

RSW - forced oscillation in pitch  
Mach 0.82



BSCW - forced oscillation in pitch, Mach 0.85

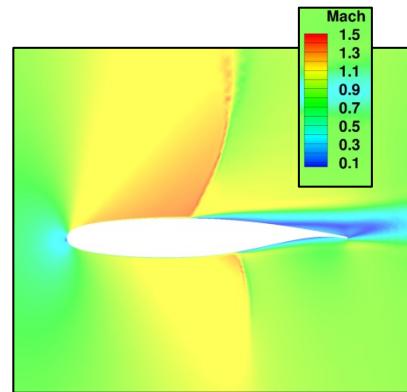
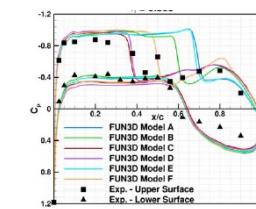
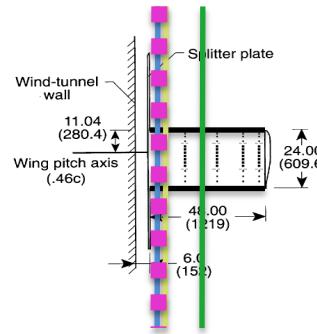


HIRENASD

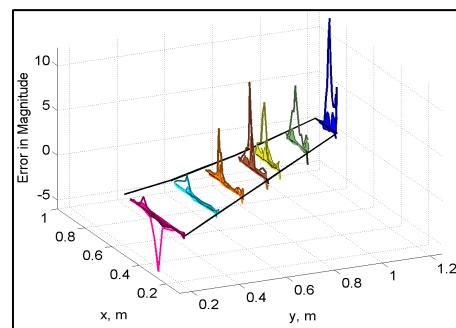
HIRENASD - excited at 2<sup>nd</sup> bending mode frequency, Mach 0.7, 0.8



# Results from AePW-1



Separated flow effects  
dominated this data set



Statistical and error analyses performed

Wind tunnel wall effects  
dominated this data set

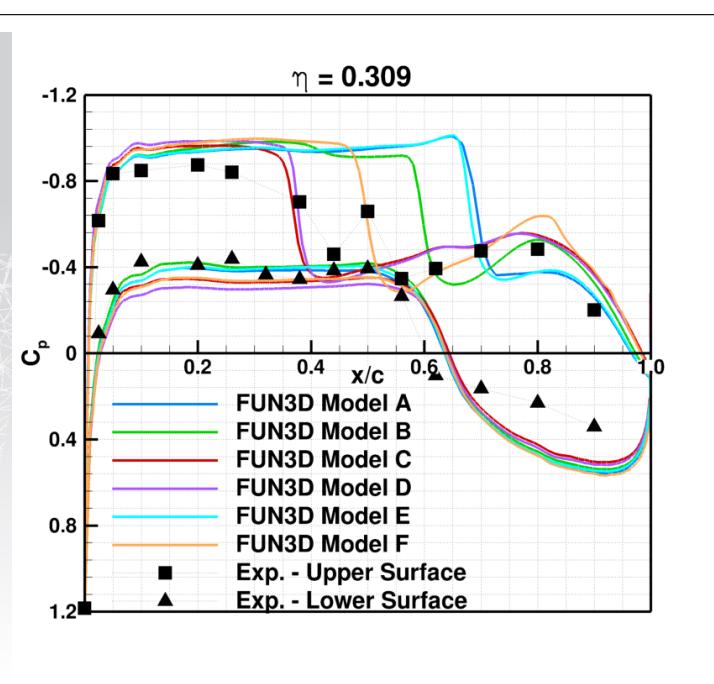
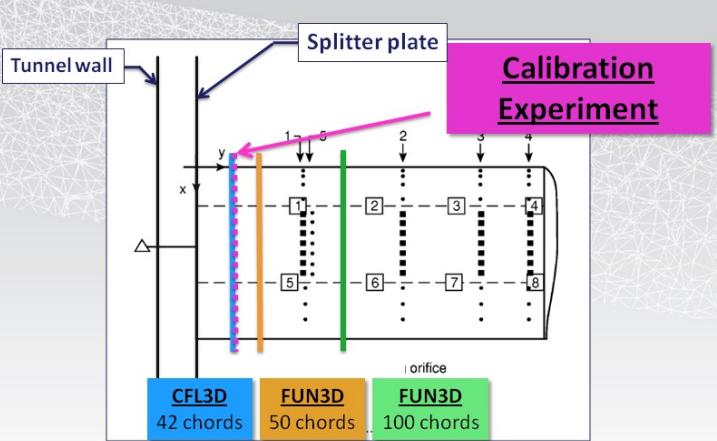


# Results from AePW-1: RSW



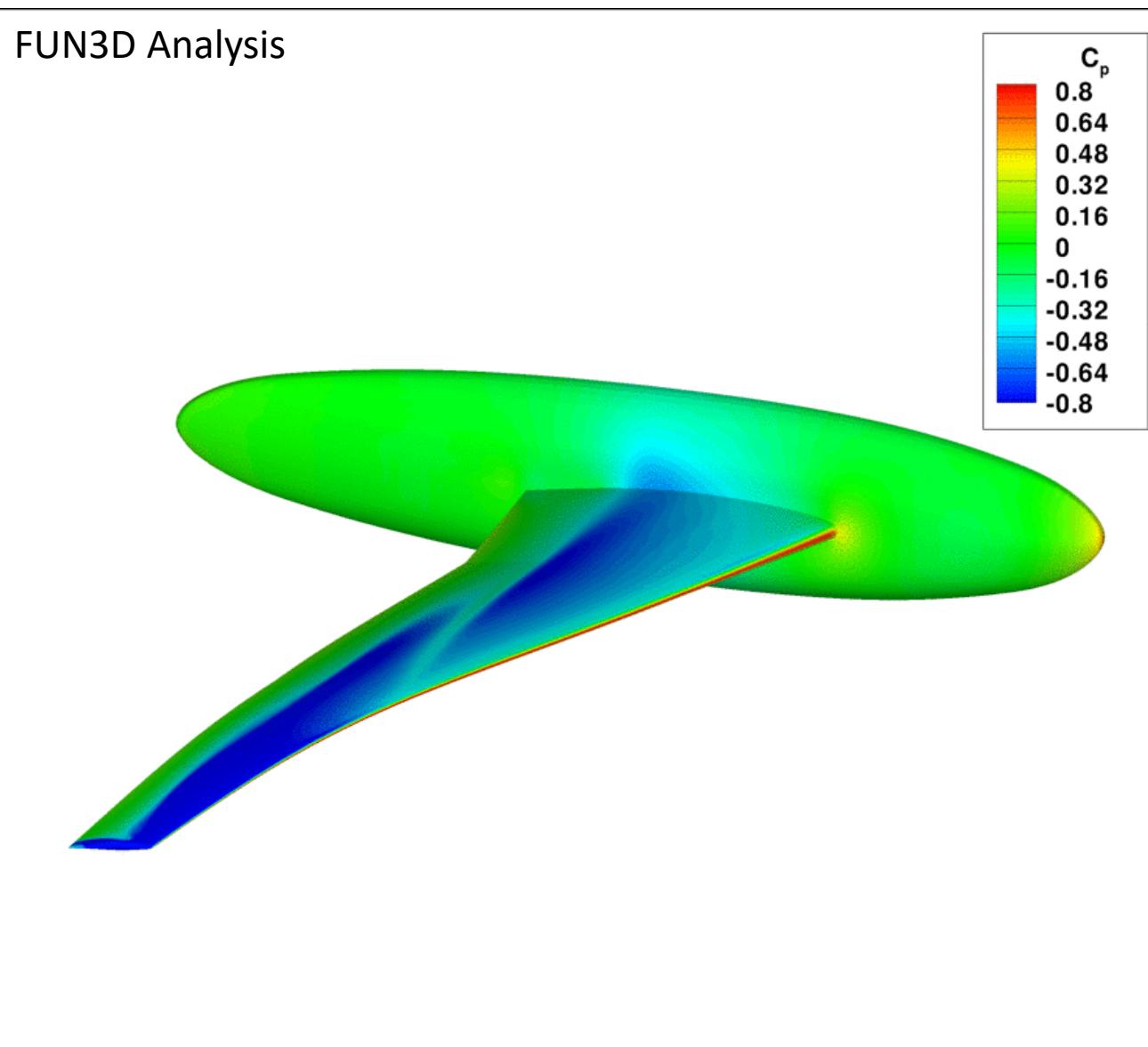
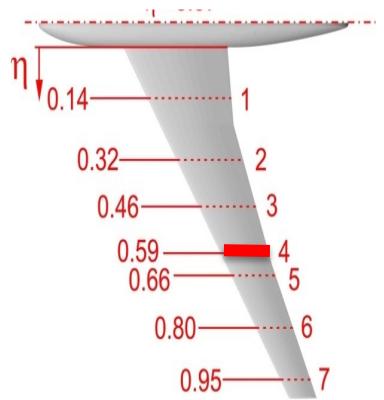
Wind tunnel wall effects dominated this data set !!!

## Wind Tunnel Wall Boundary Layer Comparisons

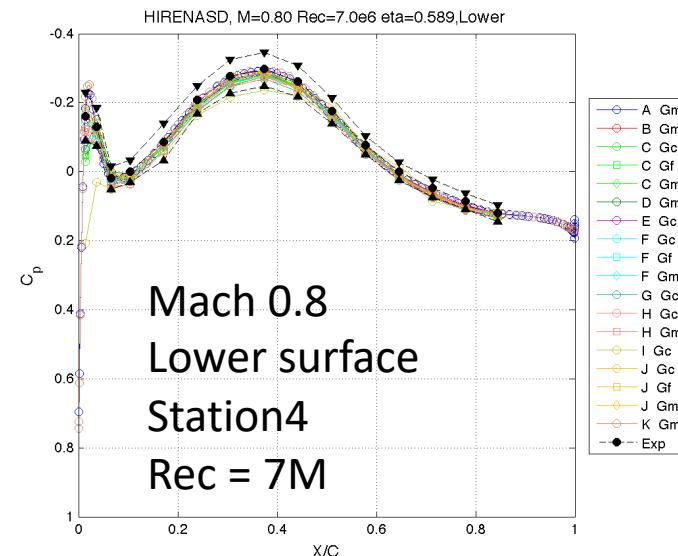
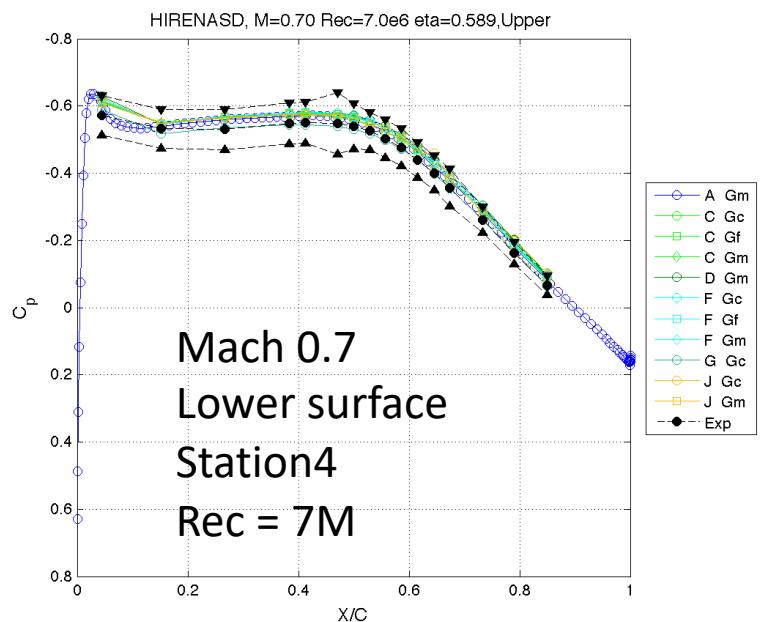
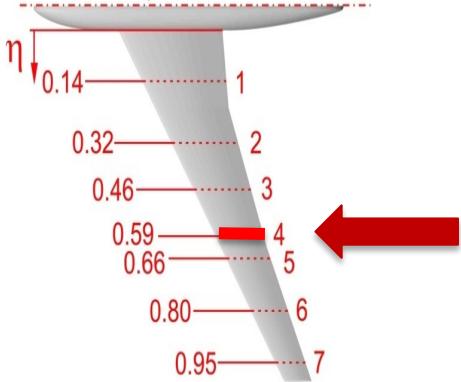
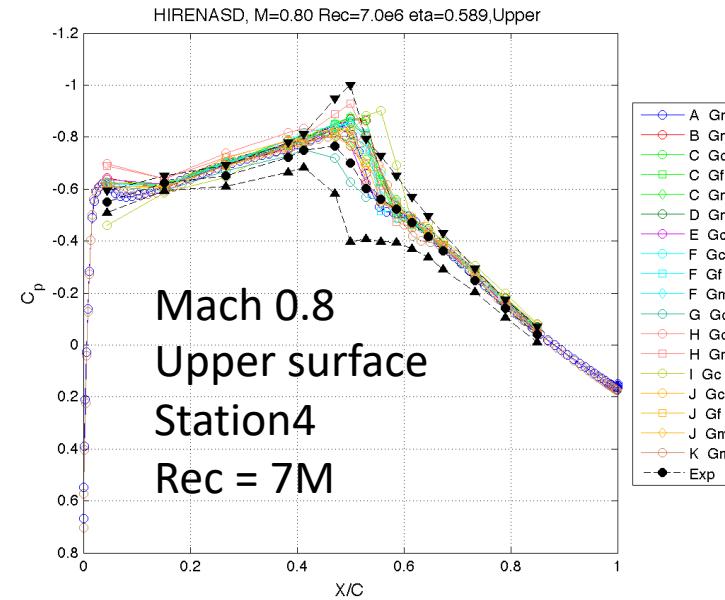
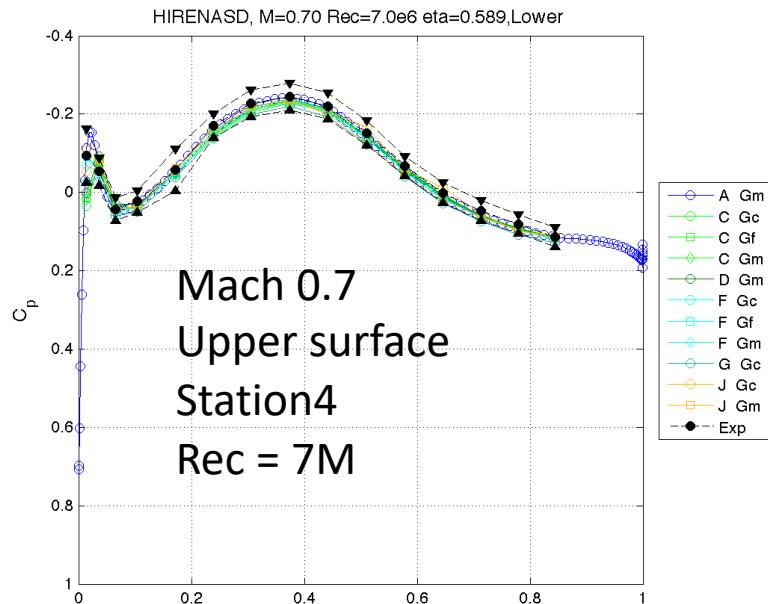


# Results from AePW-1:

Good agreement between experiment and computations

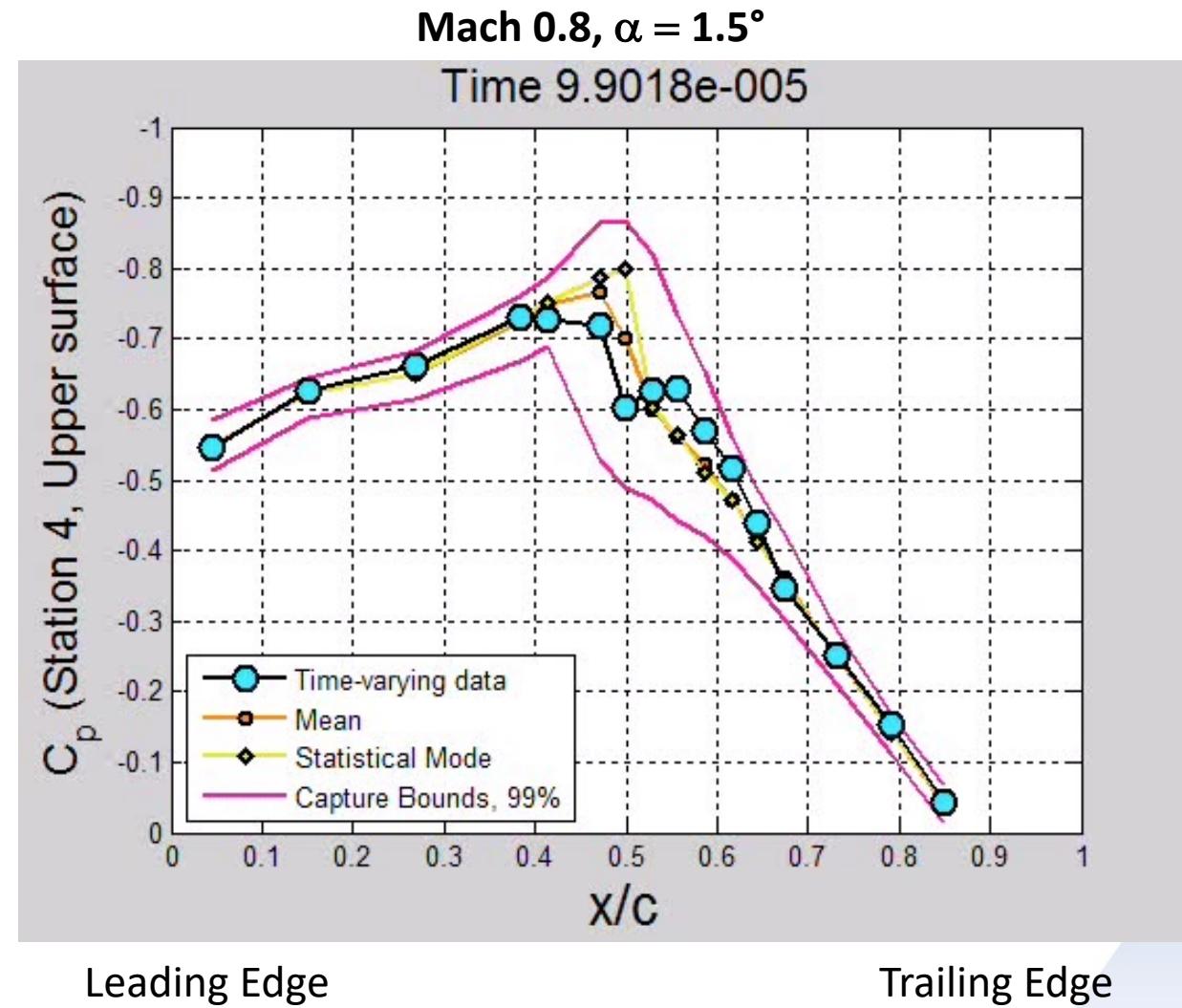
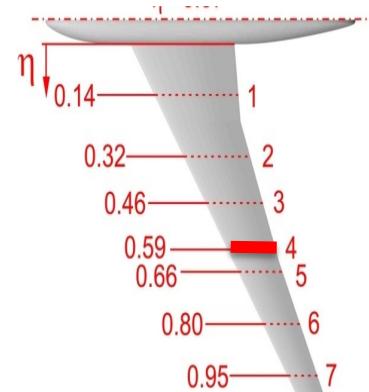


# Results from AePW-1: Good agreement between experiment and computations



# Results from AePW-1:

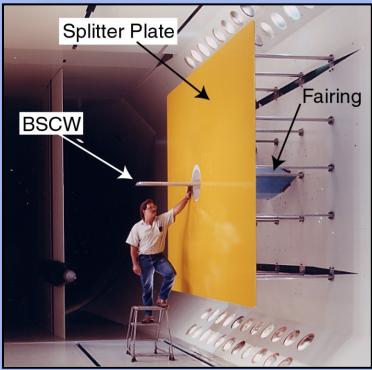
Validation data needs to be time history data, not averaged data





# Results from AePW-1:

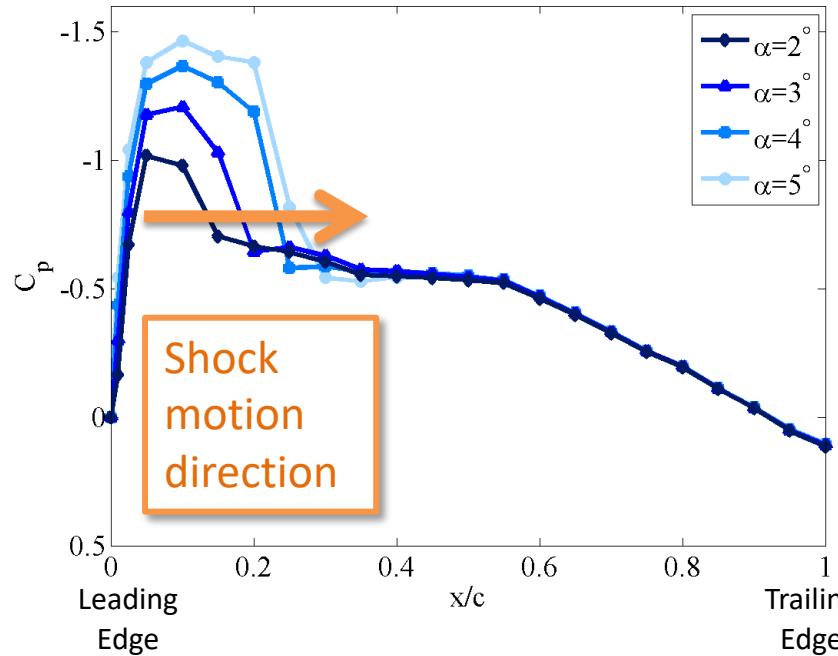
## Critical Effects of Separated Flow Benchmark Supercritical Wing (BSCW)



### Upper surface pressure coefficient distributions at 60% span

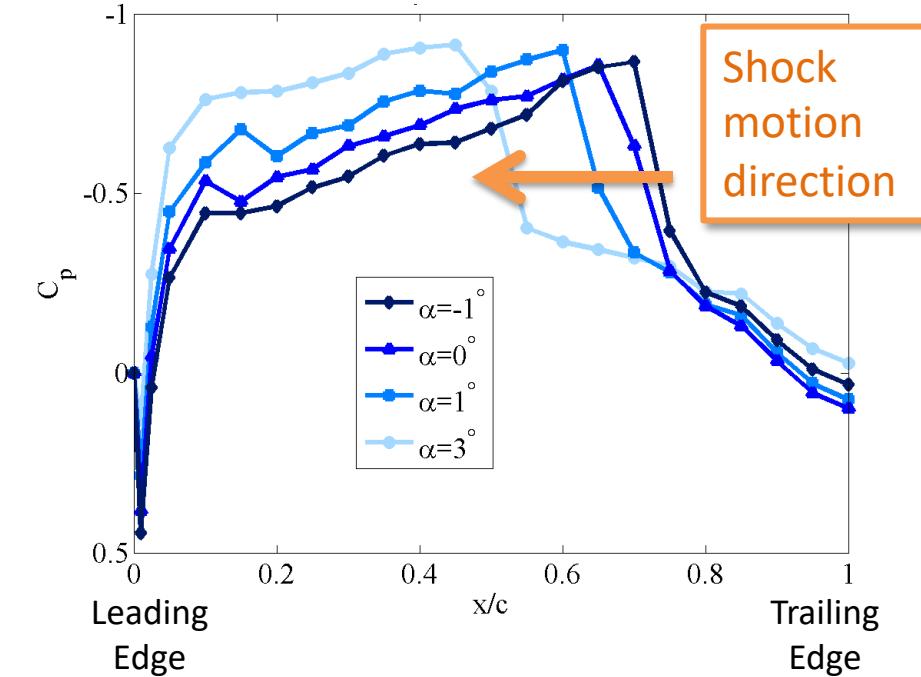
**Mach 0.74:** Attached flow

As  $\alpha$  increases, Shock moves AFT



**Mach 0.88:** Separated flow

As  $\alpha$  increases, Shock moves FORWARD



- The results echo CFD 2030 finding that “The accuracy of CFD in the aerospace design process is severely limited by the inability to reliably predict turbulent flows with significant regions of separation.”



- **What did we learn about test case selection?**

- There were too many test cases in this workshop. The number of configurations-3 - diluted the potential lessons learned for any single configuration and made it exhausting for the analysis teams.
- Have a benchmark test case. While choosing a challenging case is a good thing, choosing a first test condition for putting a stake in the sand is essential. In midanalysis cycle we added the Mach 0.7 case for the HIRENASD configuration. For those who had not previously analyzed the HIRENASD, this provided a good checkout case for their procedures and parameter selections. We should have done the same thing for the BSCW case. To rectify this, we are making an experimental data set at Mach 0.7 at a lower angle of attack available to analysts. This new benchmark case has transonic flow and oscillating shock but does not contain separated flow.



- **What have we learned regarding postprocessing of computational data?**

- The amount of information generated in performing an unsteady CFD calculation is generally insufficient for performing computations when the frequency of the response is not exactly known and exactly captured in an integer number of data samples. Fourier analysis of linear system responses are fine and the number of cycles does not have to be excessive.
- Typically, computational solutions are not run for a sufficient amount of time to utilize classical techniques for assessing and reducing the errors in the Fourier coefficients.
- The data processing for CFD data is significantly different from classical experimental data processing. It is much more reminiscent of processing signals generated from a multisine signal. The results are highly sensitive to exactly capturing single cycles and setting the Fourier block size to match.
- Classical Fourier analysis techniques may not be sufficient for analysis of CFD data that consists of limited sample sizes and short time records. New techniques that can be equally applied to both CFD and experimental data should be investigated.



- **What have we learned regarding experimental data?**

- “Steady” is a misnomer, particularly in the case of experimental data, but also perhaps in the case of computational data. The “steady” data were acquired from wind tunnel models that were sitting in the freestream turbulent wind tunnel flow field. These unforced systems generated data that contained oscillatory shock motion, oscillating regions of separated flow, influences of structural dynamic and facility aerodynamic modes.
- Using the mean value to capture a pressure distribution where there is an oscillatory shock results in smearing, canting and magnitude reduction of the pressures in the region of the shock. Mean value representations even for the unforced system should incorporate maximum and minimum bounds if nothing more descriptive.
- A validation data set should contain repeat data points and small intentional variations of test parameters such as Mach, angle of attack and Reynolds number.
- An ideal data set would contain simultaneous measurements of structural deformation, integrated loads, unsteady pressures, skin friction coefficients, and off-body flow fields.
- Time-domain data for presumably steady tests should be acquired and saved.
- Wind tunnel wall boundary layer interactions may dominate a data set if the experiment is not properly designed. Measurement of facility boundary pressures and accelerations should be considered in any benchmarking test.



- **What have we learned regarding flow solvers?**

- Flow solutions that offer better fidelity in capturing turbulence, such as LES or DES, have generally been recommended in the literature for analyzing cases where “massively separated flows” exist, usually occurring at high angles of attack. The highest mean angle of attack case for the AePW was the BSCW configuration,  $\alpha = 5^\circ$ . This test case generated what was assessed as moderately separated flow. The workshop results for BSCW led to the assessment that the URANS solutions were insufficient for this case. Some analysts are pursuing higher order CFD methods for this configuration. In this case, at a moderate angle of attack, the separated flow features are significant enough to cause a qualitative change to the shock motion and qualitative changes in the aft loading. While these changes may or may not be significant for integrated loads such as lift and pitching moment coefficient, they are likely significant for assessing aeroelastic stability, which is highly dependent on phase relationships and load distribution.
- In order to get the steady pressure distribution correctly, it is essential to get the static aeroelastic deformed shape correct. Failure to do this results in effective changes in the angle of attack. Using the rigid shape, rather than the deflected aeroelastic shape resulted in overprediction of the pressure distribution.
- Methodologies for analyzing unsteady oscillatory response are not standardized. Several methods were employed, although it has not been assessed whether the difference in oscillation method was a substantial source of variations observed.



- **What were the most challenging aspects regarding our chosen configurations? What were the consequences of these aspects?**

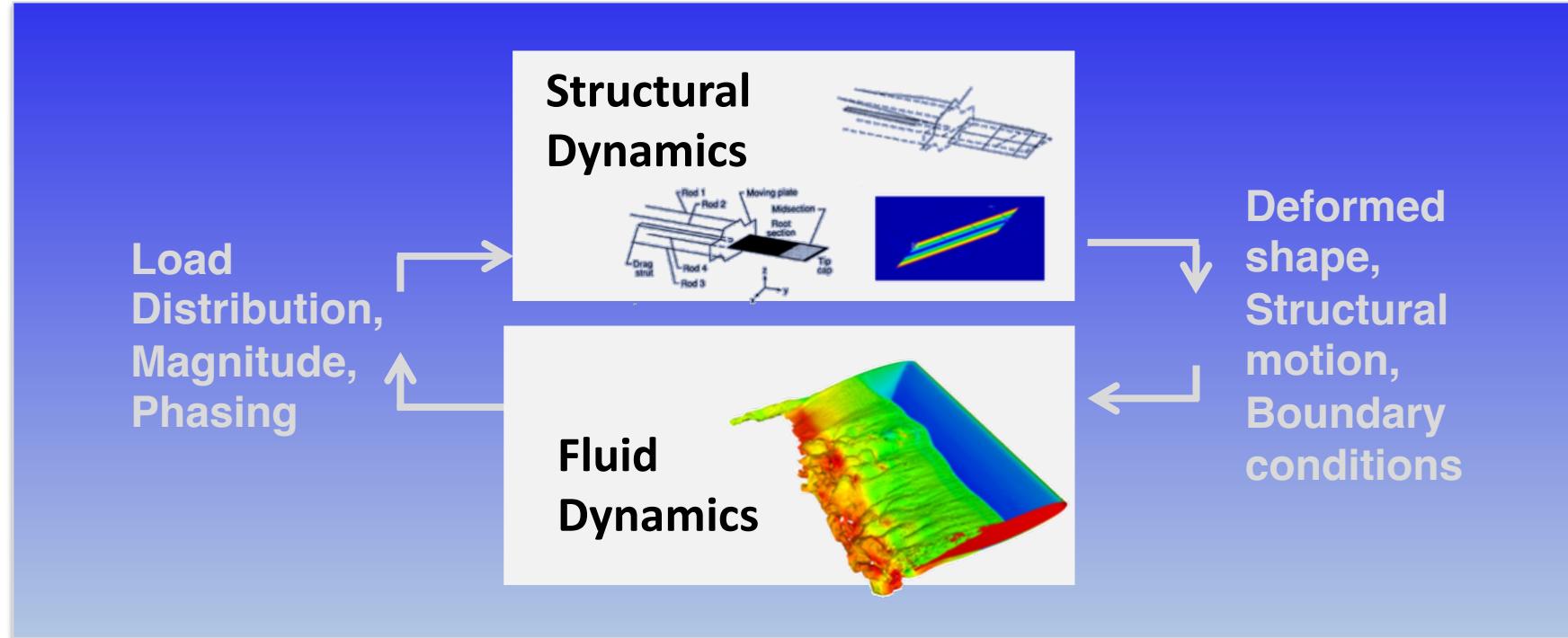
- Each of the principal test conditions for these configurations contained an oscillating upper surface shock, and in some cases a lower surface shock. The largest magnitude of the dynamics, i.e., in the FRFs, is the shock oscillation. For forced oscillation cases, the shock oscillation follows the forcing function and responds primarily at that frequency.
- The most challenging aspect of the RSW configuration was introduced by the proximity of the model to the wind tunnel wall and the undersized splitter plate. The consequence of attempting to capture the wall influences was that the CFD solutions varied widely, even for the unforced system results. We don't currently view the variation present in these results as an accurate assessment of the variation introduced by analysts' choice applicable to the state of the art.
- Shock-induced separated flow and trailing edge separation was present for the BSCW configuration at our selected test conditions. Lower surface separation in the cusp region was also likely to have occurred. The computational methods that were applied had difficulty producing converged solutions for the unforced system and for the lower frequency forced oscillation case. We have attributed the convergence problems of these solutions with the complexity of the flow field.
- HIRENASD was not as challenging as the simpler geometries of the RSW and BSCW due to test condition selection and airfoil geometry. The resulting flow physics were more easily captured by the flow solvers chosen. The zero-lift case, chosen with the thought that the shock would be less stationary, offered less of a challenge to analysts than the test case with an upper surface shock.



- **What have we learned about the state of the art in aeroelastic computations?**

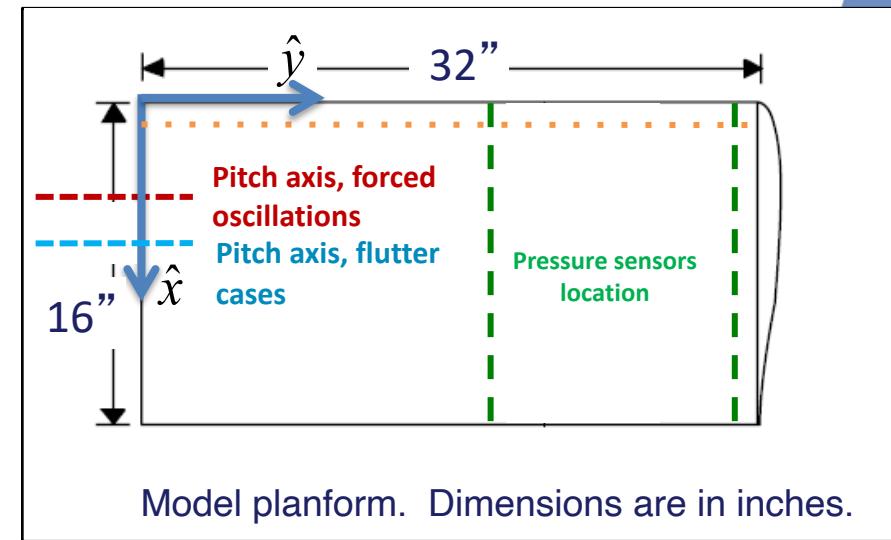
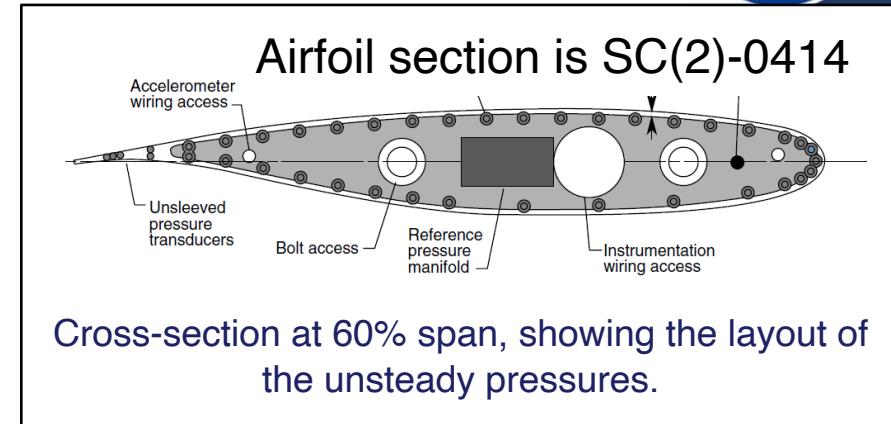
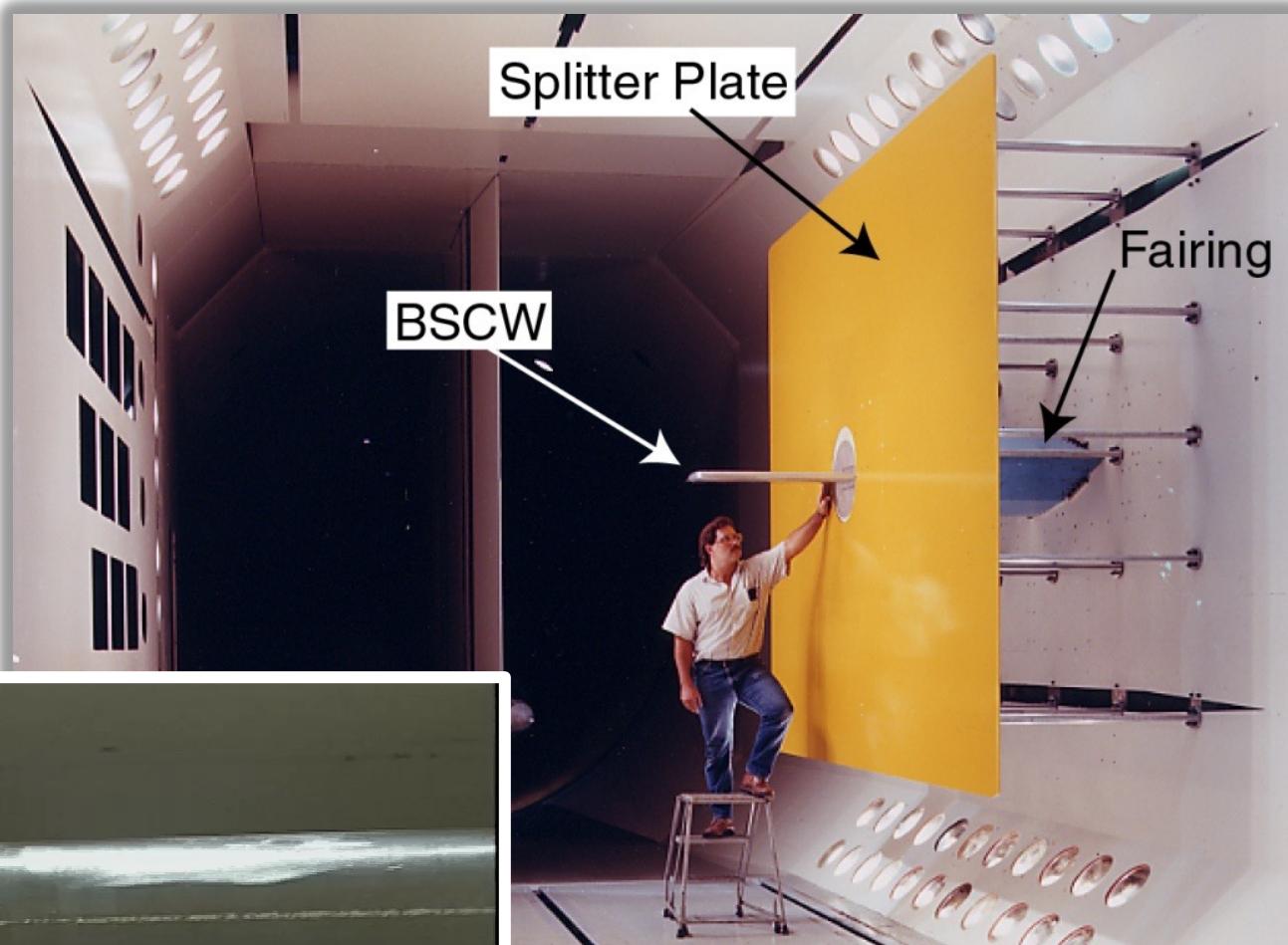
- Using RANS, we cannot accurately capture separated flow associated with the BSCW at the chosen test conditions. Although the test case was thought to contain moderately separated flow, the region of separation appears to extend from the mid-chord (shock location) to the wing trailing edge. Further, the dynamics of the flow are of essential interest in our studies. While RANS solutions may be able to predict an averaged influence of separation for small separation bubbles, they appear insufficient for either the unforced or forced oscillation responses of the BSCW configuration at Mach 0.85,  $\alpha=5^\circ$ .
- Grid refinement was not shown to improve correlation with experimental data for any of the configurations. For HIRENASD, preliminary indications are that the grid refinement did, however, reduce the variation in the predictions.
- Time step refinement was not systematically investigated by many analysts. In the few cases where it was examined and separated flow was present, qualitative changes in the results were observed.
- Modeling inconsistencies may have been responsible for the large variations observed in both the unforced system response and the frequency response functions.

# AePW Building Block Approach to Validation



**AePW-2:** Extend focus to coupled aeroelastic simulations

# AePW-2 Configuration: Benchmark Supercritical Wing (BSCW)



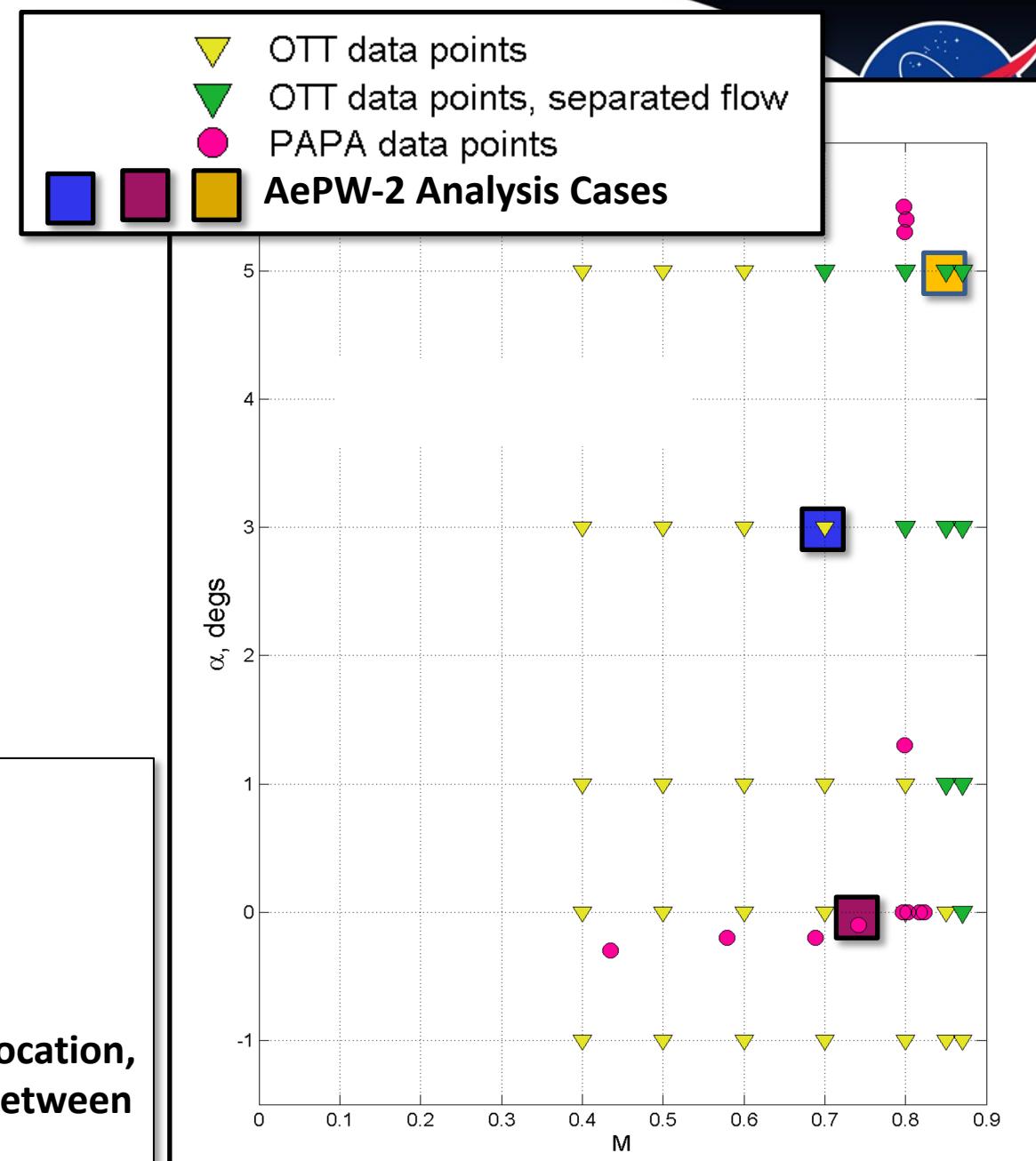
OTT: Oscillating Turn Table  
PAPA: Pitch And Plunge Apparatus

# Choosing AePW-2 Analysis Conditions

	Case 1	Case 2	Case 3
Mach	0.7	0.74	0.85
Angle of attack	3	0	5
Dynamic Data Type	Forced oscillation	Flutter	<ul style="list-style-type: none"> <li>• Unforced Unsteady</li> <li>• Forced Oscillation</li> <li>• Flutter (No exp data)</li> </ul>

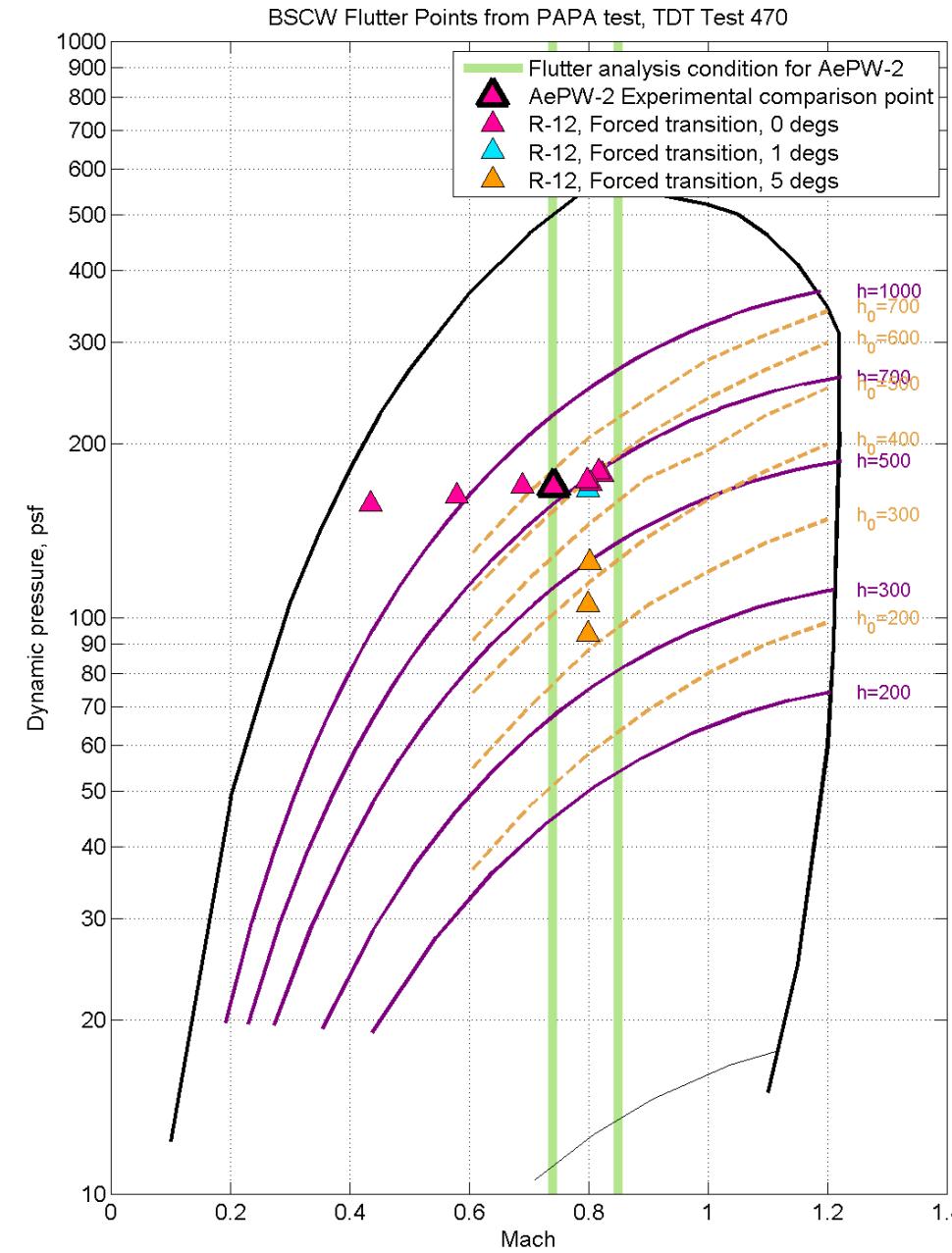
## Why these conditions?

- Cases 1 & 2:
  - A benchmark that could be analyzed with RANS
  - Quantify range of predictions
- Case 3:
  - AePW-1 showed that it was difficult, mispredicted (shock location, aft-of-shock behavior, lower surface cusp region, phasing between shock and pitch angle)
  - Why was it mispredicted?

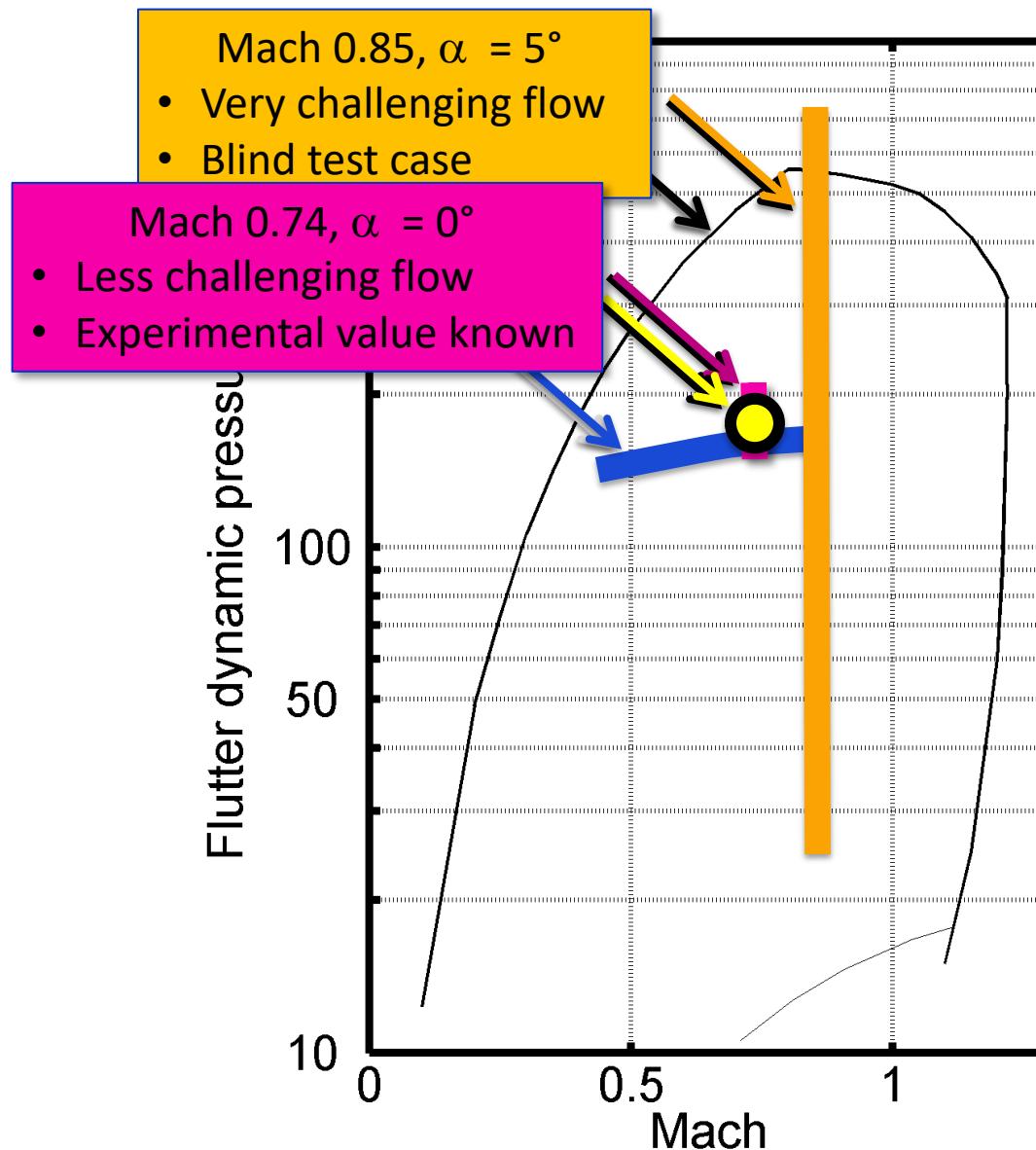


# AePW-2

## test flow conditions plotted on the TDT operating boundary in heavy gas



# AePW-2 Flutter Results Summary

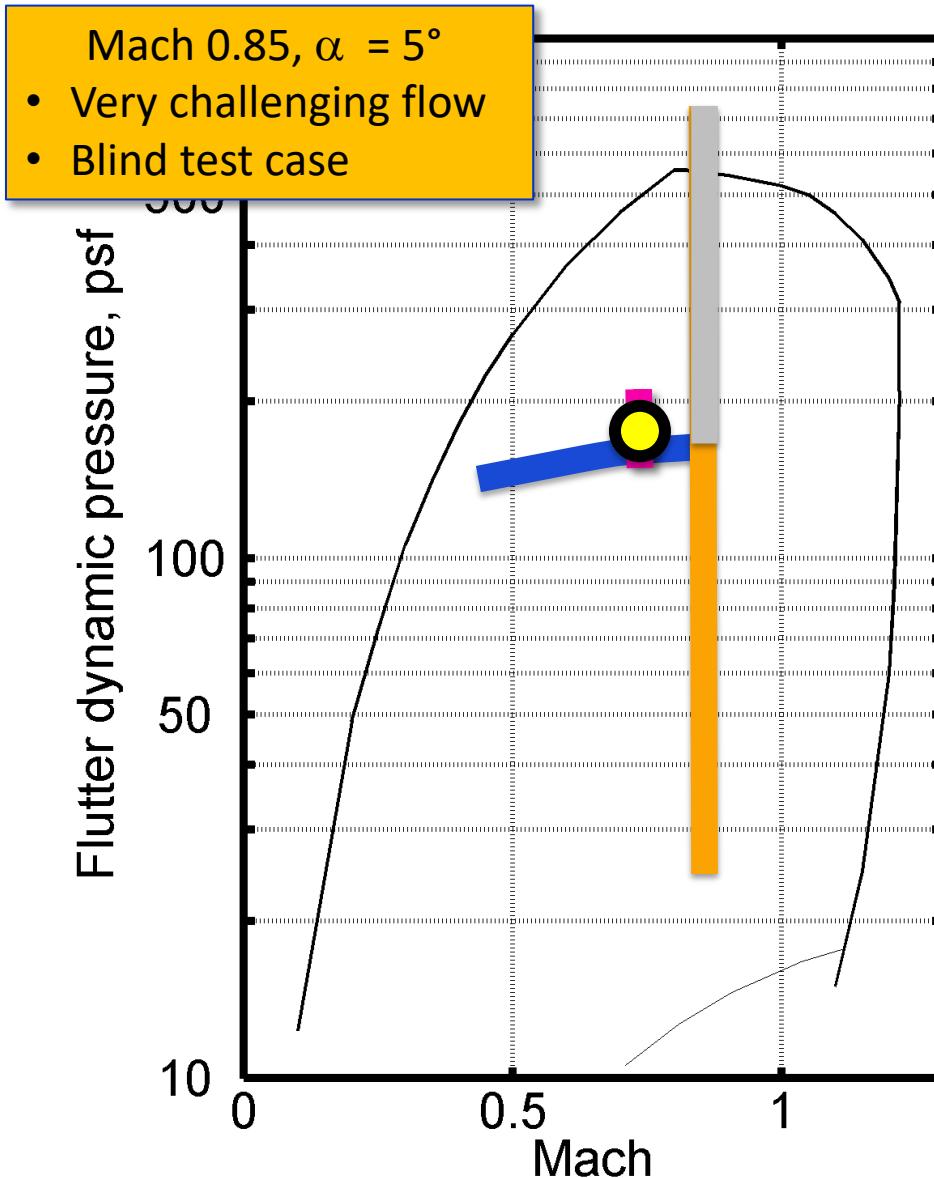


Ranges of High-Fidelity Computational Results,  
AePW-2

- **Mach 0.74,  $0^\circ$**
- **Mach 0.85,  $5^\circ$**

- **Linear Analysis Results**
- **Experiment**
- **Wind tunnel Operating Limits**

# AePW-2 Flutter Results Summary



Ranges of High-Fidelity Computational Results,  
AePW-2

- **Mach 0.74, 0°**
- **Mach 0.85, 5°**

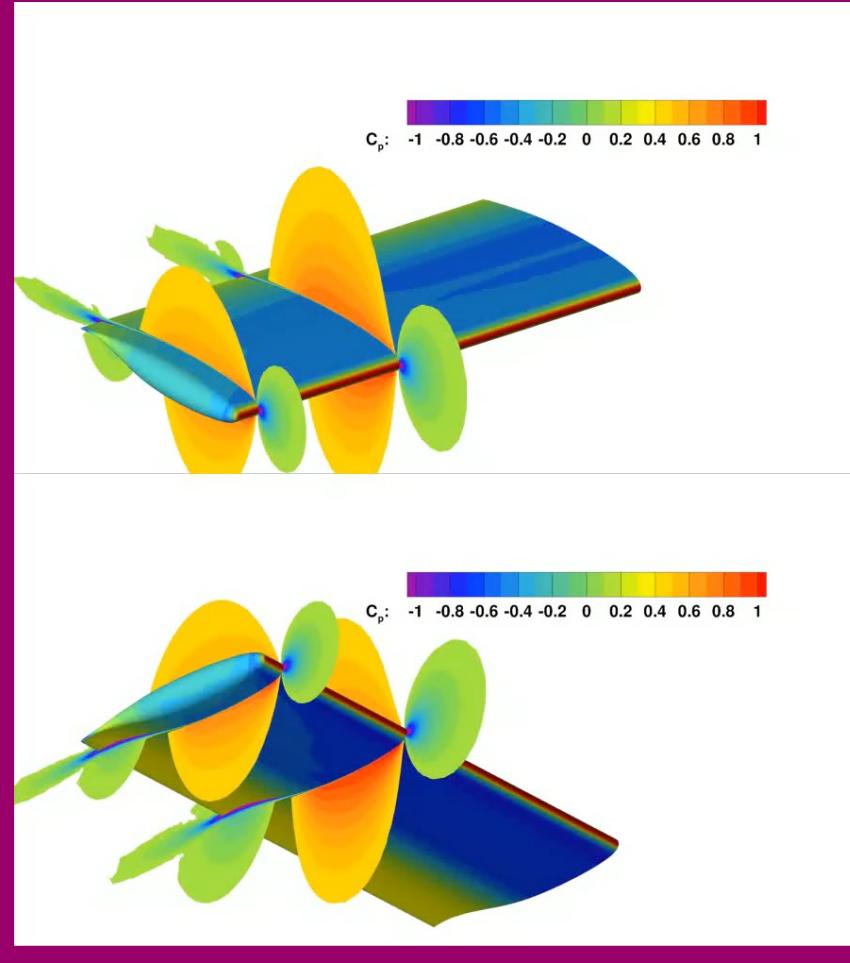
- **Linear Analysis Results**
- **Experiment**
- **Wind tunnel Operating Limits**

■ **Post workshop analysis**

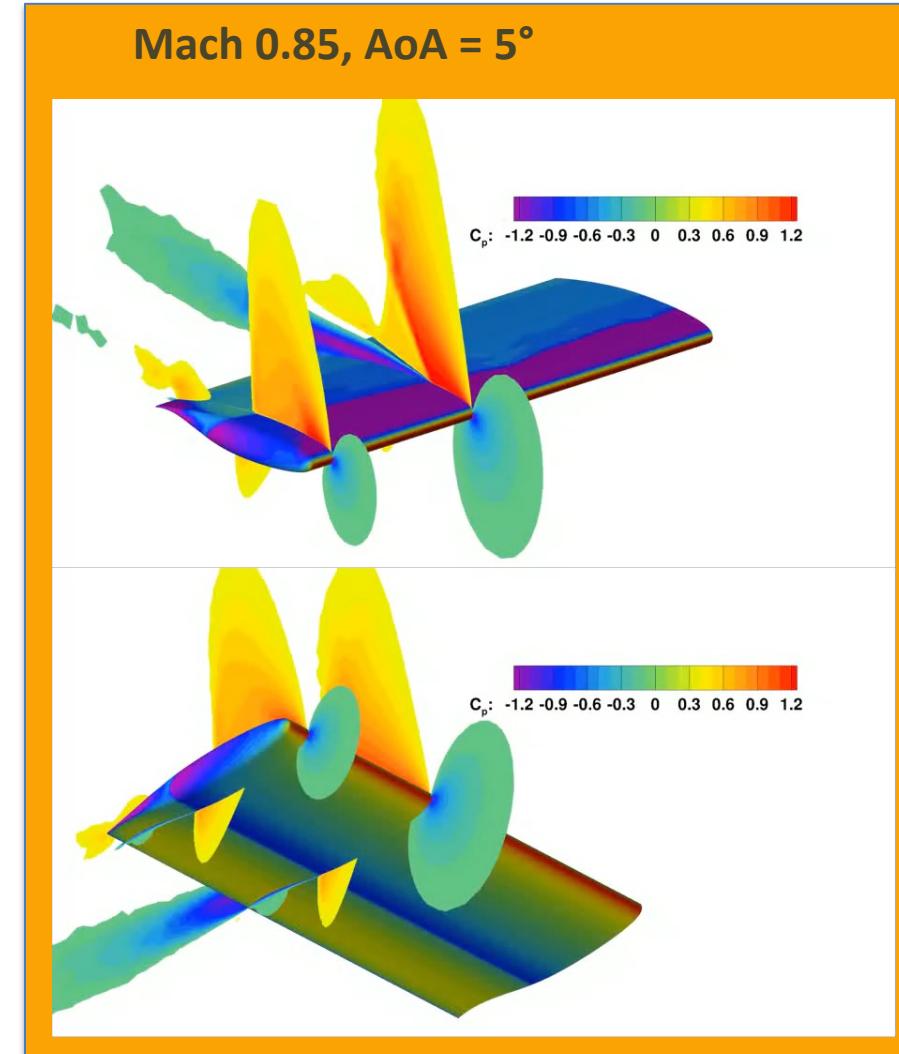
# Computational Aeroelastic Simulations, FUN3D



Mach 0.74, AoA = 0°

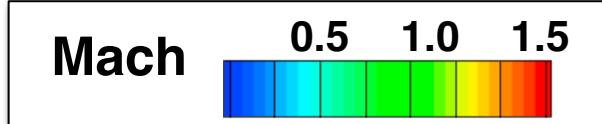


Mach 0.85, AoA = 5°



On the surfaces: colors show  $C_p$

Off the surfaces: colors show local Mach number



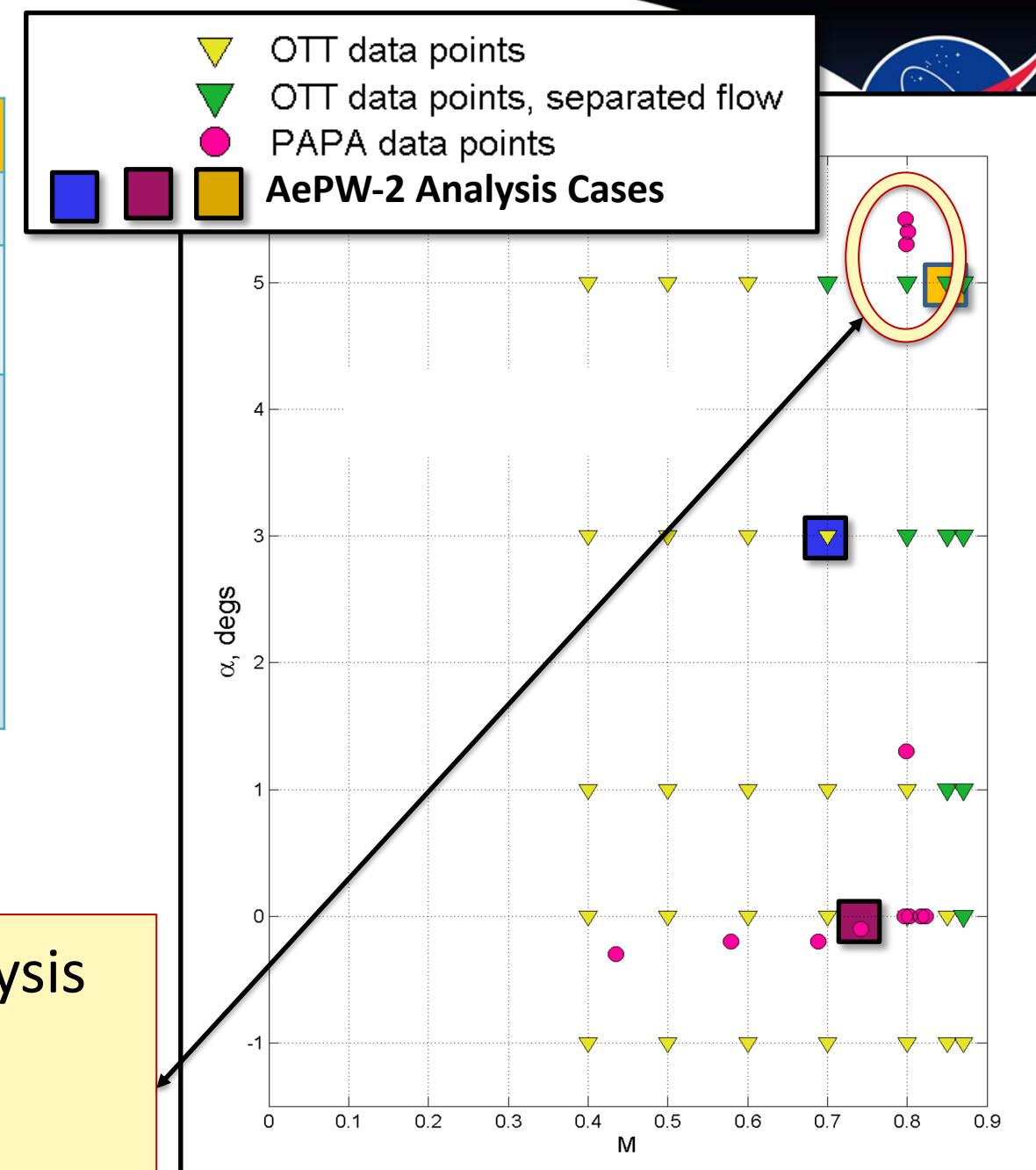
# AePW-2 Analysis Conditions

	Case 1	Case 2	Case 3
Mach	0.7	0.74	0.85
Angle of attack	3	0	5
Dynamic Data Type	Forced oscillation	Flutter	<ul style="list-style-type: none"> <li>• Unforced Unsteady</li> <li>• Forced Oscillation</li> <li>• Flutter (No exp. data)</li> </ul>



AePW-3 High Angle Working Group Analysis Conditions

Mach 0.8, AoA = 5°



# AePW-3 Working Groups



2019

Large  
Deflection

Aeroelasticity from a  
Flight Test Perspective

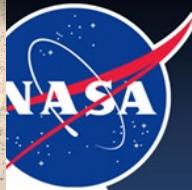
High  
Angle of Attack

Hypersonics



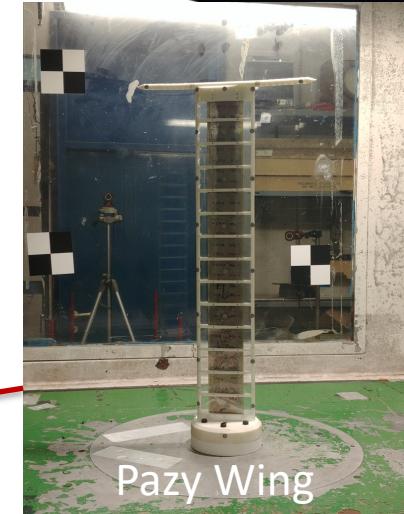
# AePW-3, SciTech 2023

<https://nescacademy.nasa.gov/workshops/AePW3/public/>



- The computational aeroelasticity community decided to split into four working groups:

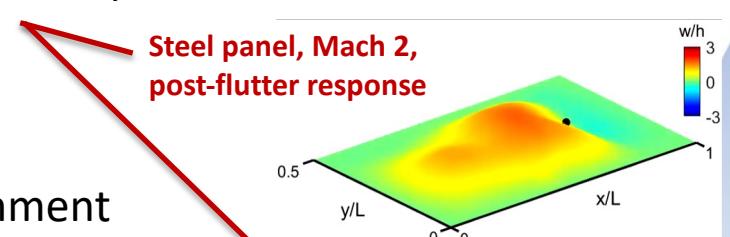
- Large Deflection:** coupled aeroelastic problems associated with large deflections of a relatively flexible high-aspect wing subjected to low-speed aerodynamics (**DLR**)



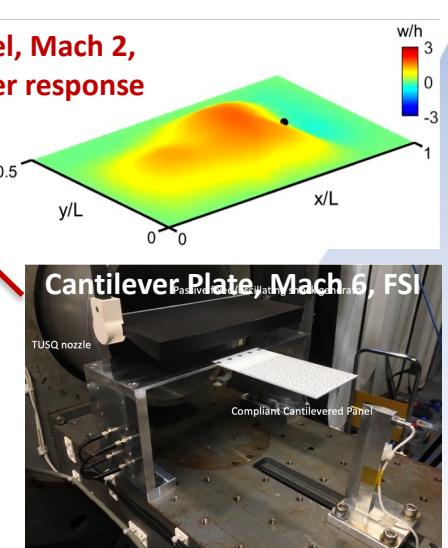
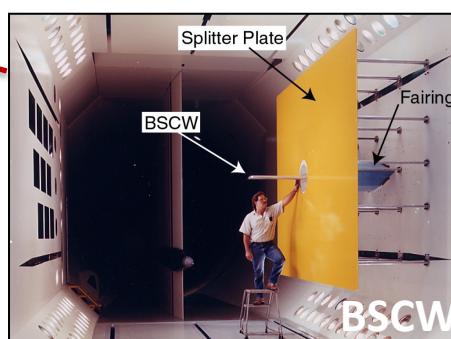
- Flight Test:** body freedom flutter analysis of NASA's experimental flight vehicle X-56A (**NASA Armstrong**)



- High Speed:** fluid-structure-interaction analysis at supersonic to hypersonic speeds (**ATA Engineering, AFRL, University of South Wales, Australia**)



- High Angle:** BSCW flutter analysis at Mach 0.8 and shock-buffet environment (**NASA Langley – Aeroelasticity Branch**)



# AePW-3, SciTech 2023 Challenges

<https://nescacademy.nasa.gov/workshops/AePW3/public/>

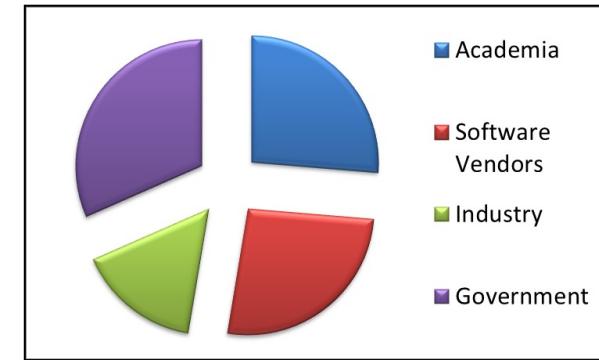


- The **flutter** instability mechanism is a key aeroelastic design metric, and requires unsteady fluid and structural analyses. For strong transonic flows, when can **uRANS** methods be used, and when are **higher-fidelity** methods required? i.e., how much flow separation can a uRANS-based flutter prediction handle?
- **Nonlinear**, hard-to-predict fluid physics (shock and boundary-layer iteration, flow separation) and structural physics (geometric nonlinearity).
- **Multidisciplinary couplings** between fluid and structure (including thermal effects, controls, etc.).
- Can Reduced Order Models (**ROMs**) or Linearized Frequency Domain (**LFD**) methods be used to expand the use of CFD-based aeroelasticity in industry? How applicable are these methods to separated fluttering flows?
- Lack of **validation experiments**, due to the **high cost** and **complexity** of flutter wind-tunnel tests, particularly in the transonic regime.
- Use of existing and planned wind-tunnel tests to **better understand why** our tools don't always produce successful predictions:
  - Which aspects of **the physics** are we **falling short** of predicting correctly?
  - What about **our methods** causes us to **fall short** of successful predictions?
  - Do we always have **enough test data** (full-field, surface-only, unsteady) to answer these questions?
- **Improved numerical algorithms** (strong coupling) and accelerated compute platforms (GPUs?) are needed for the truly challenging test cases.
- **Establish and motivate community** for leveraging experiences and processes.
- Establish **best practices** for using tools.



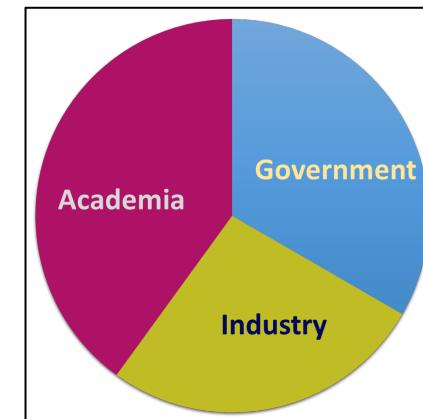
- **1<sup>st</sup> Aeroelastic Prediction Workshop (April 2012)**

- 17 analysis teams providing analysis results for workshop
- 26 total analysis sets provided
- 59 registered attendees



- **2<sup>nd</sup> Aeroelastic Prediction Workshop (January 2016)**

- 16 analysis teams providing results for the workshop
- 23 analysis methods (codes or versions of codes)
- 47 registered attendees



- **3<sup>rd</sup> Aeroelastic Prediction Workshop (January 2023)**

- 29 analysis teams
- 61 registered attendees



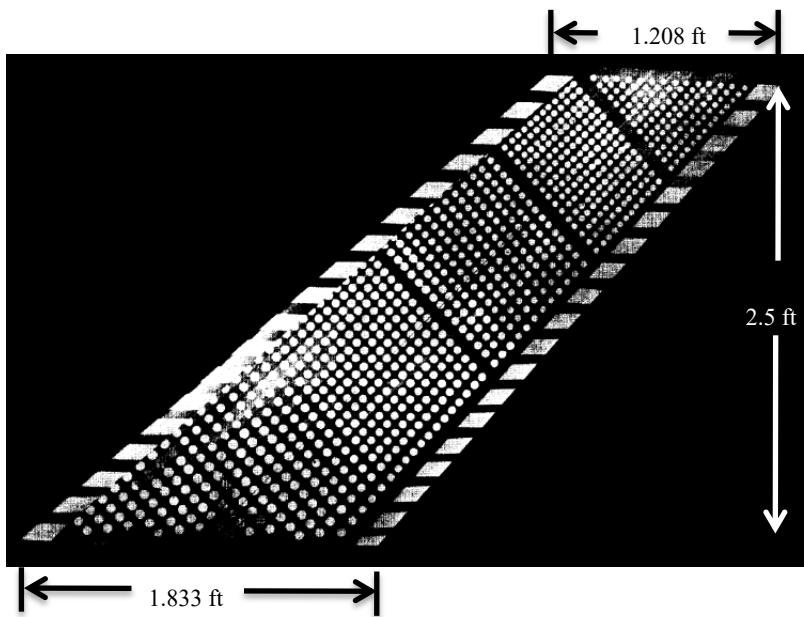
## Question ?

Transonic Dynamics Tunnel, TDT, came online in 1960.  
What was the first wing-flutter configuration tested in TDT?

# AGARD 445.6 Wing



- Tested in the TDT in 1960 by NASA Langley
- Test conditions:
  - Air and R-12 heavy gas
  - AoA = 0 deg only
  - $M = 0.34 - 1.14$
  - $Re = 0.5 - 6.7$  million



Planview of AGARD 445.6 Wing